# Origin of subthreshold $K^+$ production in heavy ion collisions

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We investigate the origin of subthreshold $K^+$ production in heavy ion collisions at intermediate energies. In particular we study the influence of the pion induced $K^+$ creation processes. We find that this channel shows a strong dependence on the size of the system, i.e., the number of participating nucleons as well as on the incident energy of the reaction. In an energy region between 1–2 GeV/nucleon the pion induced processes essentially contribute to the total yield and can even become dominant in reactions with a large number of participating nucleons. Thus we are able to reproduce recent measurements of the KaoS Collaboration for 1 GeV/nucleon Au on Au reactions adopting a realistic momentum dependent nuclear mean field.

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Since strange particles, in particular the $K^+$ meson, are considered to be well adapted to study the properties of compressed and excited nuclear matter produced in heavy ion collisions [1] strong efforts have been made in recent years concerning the measurement of kaon observables in intermediate energy reactions [2,3]. These subthreshold $K^+$ mesons are predominantly produced in the early phase of the nuclear reaction and survive, in contrast to, e.g., pions, nearly undistorted by final state interactions. Thus, $K^+$ mesons provide a direct source of information about the hot and compressed phase and have furthermore found to be sensitive on the nuclear equation of state (EOS) [4,5]. Transport models, e.g. BUU or QMD calculations, have been successful in the description of both, kaon [4–7] and pion [8,9] yields and spectra.

As a common feature of most theoretical calculations $K^+$ abundances and spectra strongly support a soft EOS [4,5,7] whereas pions are less sensitive to the nuclear EOS [8,9]. Repulsive nuclear forces in general reduce the compression reached in the high density phase of the reaction and the number of elastic and inelastic scattering processes. Hence the kaon yield is reduced as well [5,7]. However, the reproduction of nuclear flow observables requires more repulsive mean fields which in particular should take into account the momentum dependence of the nuclear interaction [10,11]. Thus, there appears to be a contradiction in model calculations with respect to different observables.

The creation mechanism of $K^+$ mesons can be divided into two classes of relevant processes, i.e., baryon induced processes

$$BB \longrightarrow BYK^+ \tag{1}$$

where the kaon is created via binary baryon–baryon collisions ($B$ stands either for a nucleon or a $\Delta$–resonance and $Y$ for a $\Lambda$ or a $\Sigma$ hyperon, respectively) and processes

$$\pi B \longrightarrow YK^+ \tag{2}$$

induced by pion absorption.

In most previous theoretical studies on subthreshold $K^+$ production only the primary processes have been considered, so, e.g., in Refs. [4–7]. The elementary cross sections used in standard transport calculations are those given by Randrup and Ko [12] which we also apply in the present work. (Although recent proton–proton scattering data [13] indicate that these might overpredict the $K^+$ production near threshold we do not assume the total yields too much to be affected by this uncertainty.) As a general result it was found that the creation process is strongly dominated by the $\Delta$–channels [4–6,14] since the $\Delta$–resonance serves as an energy storage for the creation mechanism. Furthermore, it was observed that the kaon yield significantly depends on the EOS, i.e., a soft EOS enhances the abundancies [1,5–7,14]. This statement also holds for the relativistic BUU approach of [6,7] where the repulsion of the model can be interpreted in terms of the model dependent effective nucleon mass $m^*$, see also Ref. [15]. Most of these calculations required a weakly repulsive nuclear mean field in order to reproduce the experimental kaon data [4,5,7]. Recent studies [16] further indicate that the kaon transverse flow might be sensitive on the medium dependence of the kaon dispersion relation which naturally can be expressed in scalar and vector mean fields. However, the magnitude of these fields and a reduction of the in-medium kaon mass as well as a possible shift of the respective thresholds are still a question of current debate [17]. Anyway, such a shift produced by a kaon potential will equally appear in both, baryon and pion induced channels and thus not significantly affect their balance. Hence in the present work we do not take into account such a potential.

Due to the dominance of the $\Delta$–channel in baryon induced processes the importance of the pionic channel is a question of general interest. As we show in the following the relevance of pion induced processes strongly depends

on the incident energy and the number of participant nucleons $A_{\rm part}$ which is understandable since the number of available pions strongly increases with $A_{\rm part}$ [8]. In Ref. [14] it is claimed that these channels contribute less than 25% to the total kaon yield. However, in Ref. [14] only one particular system, i.e., a central Ca+Ca collision at 0.8 GeV/nucleon has been considered. In Ref. [19] a similar analysis was performed for the Au on Au system. However, as in Ref. [14] the $\pi\Delta$ channel was not included there and thus the pionic channel was generally underpredicted. Further in [19] the influence of the initialization on the kaon yield was investigated. We also tested this with respect to the treatment of the boost procedure to the center-of-mass frame of the nuclei and observed a general uncertainity of about 20% on the total kaon yield. However, the balance of the baryon and pion induced channels was thereby nearly unaffected and thus we apply the treatment of Ref. [5].

In the present work we study the origin of the $K^+$ mass dependence, i.e. the respective multiplicities within the framework of Quantum Molecular Dynamics (QMD). As the nuclear mean field a soft Skyrme force (K=200 MeV) with momentum dependent interactions (SMD) adjusted to the empirical nucleon–nucleus optical potential is used [5,9]. Thus we apply an interaction which is able to reasonably reproduce intermediate energy nucleon flow data [10]. Pions are produced by the decay of $\Delta(1232)$ and $N^*(1440)$ resonances which are the dominant channels in the 1 GeV domain [8]. We take the isospin dependence of the respective creation and absorption channels explicitely into account. A detailed description can be found in Ref. [9]. Kaons are treated perturbatively, i.e. they do not influence the reaction dynamics, similar as described in Ref. [18]. This method is justified by the small number of kaons and the lack of reabsorption due to strangeness conservation. However, they are propagated and can undergo elastic rescattering with the surrounding nucleons.

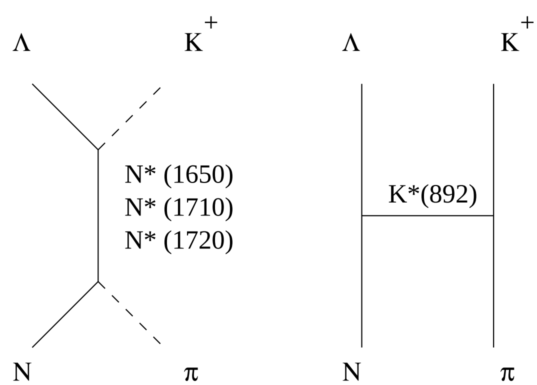


FIG. 1. Diagrams which contribute to the $\pi N \longrightarrow \Lambda K^+$ reaction and which are included in the cross section given in Eq. (3). In the left graph each $N^*$ intermediate state corresponds to a seperate diagram.

In the creation processes, Eqs. (1) and (2), we include $\Lambda$ and $\Sigma$ final state hyperons. The elementary cross sections for pion induced reactions, Eq. (2), are those given by Tsushima et al. [20,21] which are determined in the so-called resonance model. In this model the resonances $N^*(1650)(J=\frac{1}{2}^-)$, $N^*(1710)(\frac{1}{2}^+)$, $N^*(1720)(\frac{3}{2}^+)$ and $\Delta(1920)(\frac{3}{2}^+)$ are included as intermediate states. Besides these resonances in the $s$–channel, the $t$–channel $K^*(892)$–exchange is included providing a smooth background. The relevant coupling constants for baryon–meson vertices are thereby determined from the respective decay branching ratios of the resonances. This approach is able to reproduce the experimental $\pi N \longrightarrow YK^+$ free scattering data. The corresponding cross sections including a $\Sigma$ final state hyperon, i.e., $\pi^+p \longrightarrow \Sigma^+K^+$, $\pi^-p \longrightarrow \Sigma^-K^+$, $\pi^+n \longrightarrow \Sigma^0K^+$, $\pi^0n \longrightarrow \Sigma^-K^+$ and $\pi^0p \longrightarrow \Sigma^0K^+$ can be found in Ref. [20]. The cross sections for the $\Delta$–channel, i.e., $\pi^-\Delta^{++} \longrightarrow \Lambda K^+$ and $\pi^-\Delta^{++} \longrightarrow \Sigma^0K^+$, $\pi^0\Delta^0 \longrightarrow \Sigma^-K^+$, $\pi^+\Delta^0 \longrightarrow \Sigma^0K^+$ and $\pi^+\Delta^- \longrightarrow \Sigma^-K^+$ are given in [21]. For $\pi^0p \longrightarrow \Lambda K^+$ the resonance model yields [22]

$$\sigma_{\pi^0 p\longrightarrow\Lambda K^+} = \frac{1}{2}\frac{0.02279(\sqrt{s}-1.613)^{0.3894}}{(\sqrt{s}-1.700)^2+0.01031} \quad \text{mb} \tag{3}$$

where the diagrams shown in Fig.1 have been taken into account. In (3) $\sqrt{s}$ is given in GeV. From the above processes all other isospin channels can be evaluated. In contrast to the isospin averaged parametrizations of Ref. [23] these cross sections expilcitely distinguish the isospin. This fact is of importance with respect to the strong isospin dependence of pion abundances in systems with small Z/A ratios.

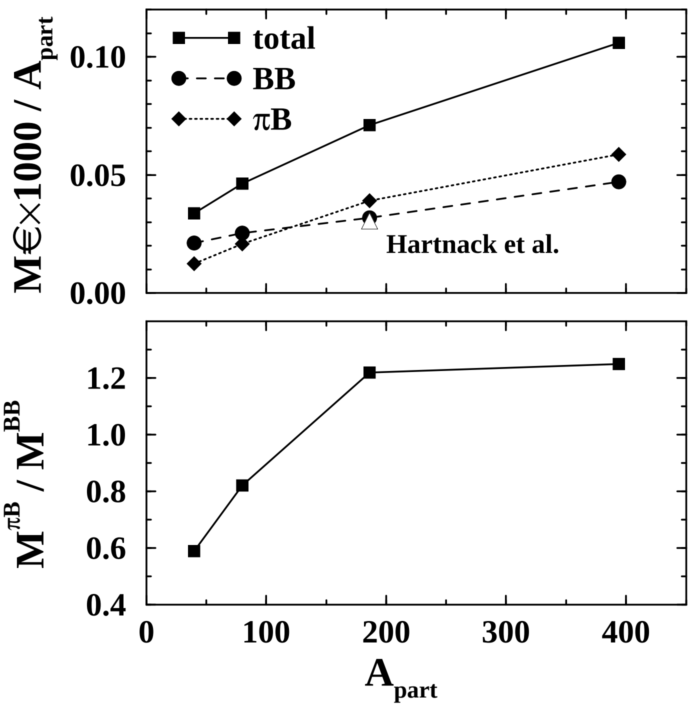


FIG. 2. $K^+$ mass dependence on the number of participating nucleons $A_{\rm part}$. The upper part shows the total $K^+$ yield (squares) and the respective contributions from baryon–baryon (circles) and pion–baryon (diamonds) induced processes in central Ne+Ne, Ca+Ca, Nb+Nb and Au+Au collisions at 1 GeV/nucleon. The calculations have been performed with a soft momentum dependent Skyrme force. In addition the result of Ref. [5] is shown (triangle). The lower part shows the ratio of kaons stemming from pion–baryon/baryon–baryon scattering processes.

First we examine the mass dependence of the $K^+$ yield. In Fig.2 (upper part) we show the $K^+$ multiplicities normalized to the number of participating nucleons $M_K/A_{\rm part}$ obtained in central collisions (b=0 fm) at 1 GeV/nucleon for four different symmetric systems, i.e., Ne+Ne, Ca+Ca, Nb+Nb and Au+Au. Concerning the baryon induced channel we find a good agreement with the corresponding result of Ref. [5]. We observe a general dependence $M_K \sim A^{\tau}_{\rm part}$ ($\tau = 1.61$) of the total kaon yield on the number of participating nuclei. This holds seperately for baryon ($\tau^{BB} = 1.40$, which is in fair agreement with the results of Ref. [5]) and pion ($\tau^{\pi B} = 1.69$) induced processes. In the latter case the slope is stiffer and thus we are in total closer to experiment ($\tau^{\rm exp} = 1.75 \pm 0.15$) [24]. Consistent with [14] the contribution from $\pi B$ scattering is relatively small at low $A_{\rm part}$. The prominent observation is, however, that the pion induced channels start to become dominant for participant numbers greater than $A_{\rm part} \sim 150$. This behavior is also reflected in the lower part of Fig.2 where the ratio $R = M_K^{\pi B}/M_K^{BB}$ of kaons stemming from baryon/pion induced processes is shown.

| | Soft | | Hard | | SMD | | HMD | |
|---|---|---|---|---|---|---|---|---|
| | $\mathrm{M_K^{tot}}$ | $\mathrm{M_K^{BB}}$ | $\mathrm{M_K^{tot}}$ | $\mathrm{M_K^{BB}}$ | $\mathrm{M_K^{tot}}$ | $\mathrm{M_K^{BB}}$ | $\mathrm{M_K^{tot}}$ | $\mathrm{M_K^{BB}}$ |
| Ne+Ne | 3.0 | 2.0 | 2.8 | 1.9 | 1.3 | 0.85 | 1.4 | 0.96 |
| Ca+Ca | 8.9 | 5.2 | 8.5 | 4.9 | 3.7 | 2.0 | 4.3 | 2.1 |
| Nb+Nb | 30.0 | 16.2 | 23.0 | 13.7 | 13.3 | 5.9 | 12.6 | 6.0 |
| Au+Au | 91.0 | 43.2 | 61.5 | 31.0 | 41.8 | 18.6 | 33.5 | 14.6 |

TABLE I. Dependence of the $K^+$ production on the nuclear equation of state. The same reactions as in Fig. 2 are considered. Skyrme forces corresponding to a soft/hard EOS without (Soft/Hard) and including momentum dependent interactions (SMD/HMD) are applied. $\mathrm{M_K^{tot}}$ is the total multiplicity ($\times 1000$) and $\mathrm{M_K^{BB}}$ is the contribution from baryon induced processes ($\times 1000$).

The influence of the nuclear equation of state on the kaon yield is demonstrated in Tab. 1. There we consider the same reactions as in Fig.2, however, applying different EOS's, i.e., a soft/hard EOS without and including momentum dependent interactions. It is seen that the enhancement of the kaon yield by the pion induced channels is a general feature which is rather indepent on the particular choice of the nuclear forces. The ratio $M_K^{\pi B}/M_K^{BB}$ is more or less the same in all cases. As already observed in previous works [4,5,7,14] the kaon yield is generally enhanced using a soft EOS. This effect is most pronounced in heavy systems. We further find an overall good agreement with the results of Ref. [5] (Fig.9 given therein) concerning the contributions from baryon induced $K^+$ production. However, the total kaon yield is stronly reduced by the momentum dependent interactions (SMD/HMD). Then the stiffness of the EOS (soft or hard) is even of minor importance which is due to the fact that the repulsion of the interaction originates to most extent from their momentum dependence. In the following we restrict the discussion to realistic nuclear interactions, i.e., to momentum dependent forces (SMD).

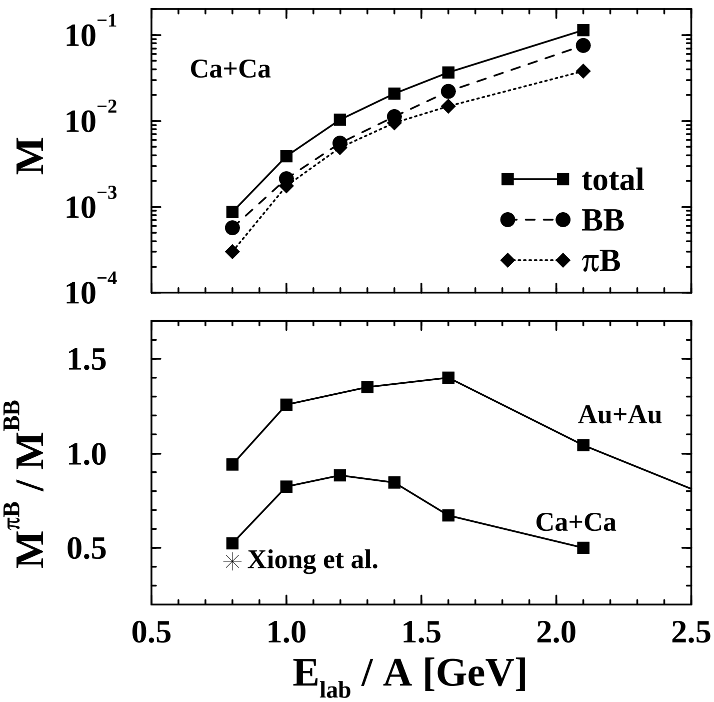


FIG. 3. Energy dependence of the $K^+$ yield. As in Fig. 2 the contributions from baryon–baryon (circles) and pion–baryon (diamonds) induced processes are compared to the total yield (squares) for central (b=0) Ca+Ca collisions. The lower part shows the respective ratios obtained in central Ca+Ca (b=0) and Au+Au (b=3 fm) collisions. In addition the corresponding result of Ref. [14] for Ca+Ca at 0.8 GeV/nucleon is shown.

In Fig.3 the energy dependence of the kaon production is considered. The upper part shows the kaon multiplicities for a central (b=0 fm) Ca+Ca collision at various incident energies and the lower part again shows the coresponding ratio $R$. It is clearly seen that $R$ exhibits a prominent peak around an incident energy of $E_{\rm lab} \sim 1.2$ GeV/nucleon. Below 1 GeV/nucleon the pion induced processes contribute with 30% to the total yield which coincides with the result of [14] obtained with a hard Skyrme force (K=380 MeV). Since we included more repulsive momentum dependent iteractions it is reasonable to compare to the hard EOS. Due to the lack of the $\Sigma$ channel the total yield is underpredicted in [14], however, the ratios are in good agreement. With increasing energy the $\pi B$ channel gains more importance. At $E_{\rm lab} = 1$ GeV/nucleon its contribution lies already at about 45%. It reaches a maximum of nearly 50% at 1.2 GeV/nucleon and then starts to decrease with energy. A similar behavior is observed in a system with large $A_{\rm part}$, i.e., a central (b=3 fm) Au+Au reaction. Here the peak is broadened and slightly shifted towards higher energies. Above 1 GeV/nucleon the secondary processes even start to become dominant. Between an energy range of $E_{\rm lab} \sim 1-2$ GeV/nucleon they are responsible for 55–60% of the total yield. Furthermore, a threshold behavior can be observed around 1 GeV/nucleon which can be understood in terms of the elementary cross sections. Whereas the cross sections for binary baryon–baryon collisions $\sigma_{BB\longrightarrow BYK^+}(\sqrt{s})$ are more or less linearly increasing functions with $\sqrt{s}$ [23] the respective cross sections for the pion induced channels $\sigma_{\pi B\longrightarrow YK^+}(\sqrt{s})$ are strongly peaked around $\sqrt{s} \sim 1.8-2$

GeV [20]. Also a simple consideration of the respective thresholds supports these findings. E.g. with a final $\Lambda$–hyperon the $\pi\Delta$ ($\Delta E_{\rm thres} = \sum M_{\rm final} - \sum M_{\rm initial} \approx 237$ MeV) channel is energetically favoured with respect to the $N\Delta$ ($\Delta E_{\rm thres} \approx 377$ MeV) channel. The same holds for the $\pi N$ ($\Delta E_{\rm thres} \approx 530$ MeV) with respect to the $NN$ ($\Delta E_{\rm thres} \approx 670$ MeV) channel. Providing a sufficiently high amount of pions in the system, i.e. large $A_{\rm part}$, the strong contribution from $\pi B$ near threshold and its dropping down at higher energies is understandable.

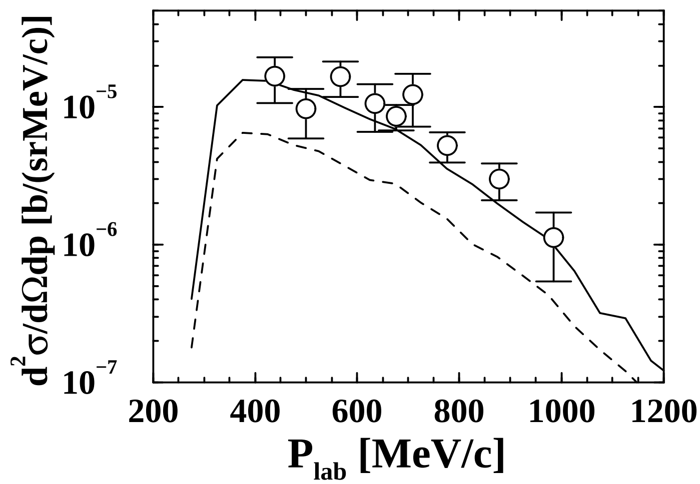


FIG. 4. $K^+$ spectrum in a Au on Au reaction at 1 GeV/nucleon under $40^\circ < \Theta_{\rm lab} < 48^\circ$. The solid line indicates the total spectrum and the dashed line the contribution only from baryon–baryon induced $K^+$ production. The data are taken from Ref. [2].

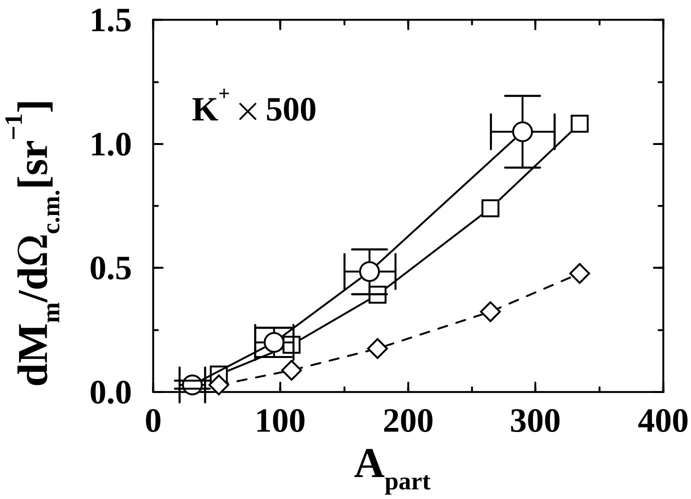


FIG. 5. $K^+$ multiplicity per center-of-mass solid angle for the same reaction as in Fig. 4 as a function of the number of participating nucleons. The total (squares) multiplicities and the respective contributions from baryon–baryon induced $K^+$ production (diamonds) are shown. The data are taken from Ref. [2].

In Fig.4 the inclusive $K^+$ kinetic spectrum measured under $40^\circ < \Theta_{\rm lab} < 48^\circ$ degrees in Au+Au reactions at 1 GeV/nucleon is shown as a function of laboratory momentum $p_{\rm lab}$. The experimental data are those from the KaoS Collaboration [2]. The calculations are performed under minimum bias condition with an acceptance cut of $0.3 < y/y_{\rm proj} < 0.6$ [2]. We are able to reasonably reproduce the data. Consistent with our previous findings, Figs.2 and 3, the inclusion only of the $BB$ channel underpredicts the data by about a factor of two. The same holds for Fig.5 where the $K^+$ multplicities as function of $A_{\rm part}$ are compared to the data [2]. Here it becomes even more evident that in the heavy system the majority of kaons stems from pion induced processes. For the total multplicities we find a slight underprediction of the data but the general trend is well reproduced, in particular the slope of the $A_{\rm part}$ dependence at high values of $A_{\rm part}$. However, the $K^+$ abundancies found in very recent measurements of KaoS with improved statistics [24] seem as well to be slightly reduced (by about 20%) compared to those given in Ref. [2].

To summarize, we have investigated the influence of pion induced $K^+$ production in heavy ion collisions. Thereby we applied the elementary cross sections determined in the resonance model and take both, $\Lambda$ and $\Sigma$ hyperon final states into account. With a realistic nuclear mean field, i.e., a soft momentum dependent Skyrme force we obtain a good agreement with present $K^+$ data from KaoS for both, spectra and multiplicities in 1 GeV/nucleon Au on Au reactions. Previous calculations which did not take into account pion induced processes required an unrealistically weak repulsion of the nuclear forces in order to reproduce the $K^+$ data, a contradiction which is now resolved. We found that the pion induced processes essentially contribute to the total yield. This appears to be a general feature which is rather independent on the particular choice of the nuclear interaction. In heavy systems, i.e., with participant numbers greater than about 150 these channels even start to become dominant. Furthermore, the pionic channels exhibit a sort of a threshold behavior around 1 GeV/nucleon incident energy and are most prominent between 1–2 GeV/nucleon which is in agreement with the energy dependence of the elementary cross sections and the respective thresholds. These results further indicate that the measurement of, e.g., $K^+/\pi^+$ correlations is most promising in an energy range between 1–2 GeV/nucleon with maximal number of participating nucleons.

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